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BEHAVIORAL PERFORMANCE IN MONKEYS EXPOSED TO TEMPO HIGH-PEAK-POWER MICROWAVE PULSES AT 3 GHz

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The animals used in this work were handled in accordance with the principles outlined in the *Guide for the Care and Use of Laboratory Animals*, prepared by the Committee on Care and Use of Laboratory Animals of the Institute of Laboratory Animal Resources, National Research Council, DHHS, NIH Publication No. 85-23, 1985; and The Animal Welfare Act of 1966, as amended in 1970 and 1976.

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ABSTRACT

The development of adequate safety standards for exposure to microwave radiation requires an extensive data base, which provides information on frequency, power, and modulation characteristics. This study was conducted to provide information on the behavioral effects of high-peak-power microwave pulses produced by an axially extracted virtual cathode oscillator. This pulsed microwave source, TEMPO[2], was located at the Walter Reed Army Institute of Research and was configured for this study to produce high-peak-power 3.0-GHz microwave pulses, 20-60 ns pulse duration with a 7.5-s interpulse interval. To investigate the behavioral effects of the high-peak-power pulses, four male rhesus monkeys (*Macaca mulatta*) were trained on a operant color discrimination task for food pellet reward. The task was twofold requiring monkeys to pull one plastic lever on a variable interval schedule (VI-25 s) and then respond to color signals and pull a second lever to obtain food. During the behavioral task, the monkeys were exposed to microwave pulses produced by TEMPO. Peak field power densities averaged 45.63 kW/cm^2, which produced a peak whole-body specific absorption rate (SAR) of approximately 2.21 MW/kg (specific absorption (SA) per pulse was 1.3 J/kg). Average whole-body SAR, however, was low due to the short pulse duration and long interpulse interval. Behavioral performance on either component of the task was not altered significantly by the high-peak-power pulses.

[2]Transformer Energized Megavolt Pulsed Output (TEMPO)

Acknowledgments

We thank Dr. Chun Y. Moon for performing dosimetry experiments on the monkey model and Delores Beblo for field power density measurements in the anechoic chamber. We also thank Peter Collyer, and Michael Blanchard for electronic graphics of figures and graphs, and Rex Dolgner for video production. Special appreciation is extended to Robert Upchurch for assisting in monkey training and the setup and conduct of the experiments. Finally, we thank Peggy Tracy for final typing of this manuscript and Kathleen Mayer for editorial assistance.

INTRODUCTION

Nonionizing electromagnetic energy (EMR) in the radiofrequency (RF) and microwave range is used heavily onboard modern U.S. Navy vessels for communication, target acquisition, electronic warfare, and other purposes. The use of EMR, for these functions is important for a modern navy. Remote deployments and significant engagement distances encountered in modern warfare rely on EMR and nearly all EMR emitters on ships have very high power output. Protection of personnel on ships or at shore stations requires avoidance of RF antennas and microwave beams or restriction to areas where there are safe levels of exposure. Recommended levels of safe exposure to RF and microwave energy have been developed (IEEE, 1991) and adopted with some modification by the Department of Defense (DODINST 6055.11). The IEEE (1991) safety recommendations, however, are not final and are revised every 5 years based on new scientific evidence. These recommendations are important to Naval Operations because the recommended safe exposure levels determine the standoff distances and safety procedures that personnel must maintain when working near RF and microwave emitters. The permissible exposure limits (PEL) to RF microwave radiation around antennas on ships are indicated by lines painted on the deck beyond which personnel should not proceed. As the PELs are reduced, the restricted area around each antenna is made larger. Unlike the other military services, significant standoff distances from such emitters onboard ship to reduce the level of exposure of personnel is not possible.

The biological effects produced by high-peak-power microwave pulses has not received much research attention. Pulsed output levels from both high-power radars and pulsed-directed energy systems has increased significantly over the past decade. The current safety standard (IEEE, 1991) limits human exposure to instantaneous peak power pulsed microwave fields at 100 kV/m ($\approx$2.65 kW/cm^2). However, previous investigations of biological effects produced by pulsed microwave energy with very high-peak-power have been very limited. A valid safety standard for exposure to high-peak-power microwave pulses can only be established from an extensive experimental data base.

In previous TEMPO studies (D'Andrea et al., 1989, 1990), there were no significant effects of 2.37- or 2.36-GHz pulsed microwaves on rhesus monkey behavior at peak power densities of 5.36-12.16 kW/cm^2 with peak whole-body SARs per pulse of 365-938 kW/kg. Because the pulse duration was low (50 to 93 ns), however, the specific absorption (SA) per pulse was only 54-87 mJ/kg. In both studies, the monkeys were exposed repeatedly to high-peak-power microwave pulses with the long axis of the animal's body aligned parallel to either the electric (D'Andrea et al., 1989) or magnetic (D'Andrea et al., 1990) field vector. Monkeys were exposed in the different orientations because microwave absorption and hotspot formation in the body depends strongly on this factor. In the study reported here, we exposed monkeys with the long axis of the body aligned parallel to the electric field vector and used higher field power densities (45.63 kW/cm^2) than previously achieved.

METHODS

SUBJECTS

Four male, juvenile rhesus monkeys (*Macaca mulatta*) obtained from Charles River Laboratories (Wilmington, MA) were used as subjects. These monkeys were certified Herpesvirus simiae (B virus) free. The mean body mass of the subjects during the study was 3.47 kg ($\pm$ 0.07 kg, *SEM*). The subjects were fed a standard primate diet (Wayne Co., 24% protein) daily in sufficient quantities (freely available in their cages)

to produce a normal-sized animal for that age. During the experiment, the animals obtained their daily food ration (BioServ, Holton Industries Co., 1-g monkey banana formula dustless pellets) while performing the experiment. Their diet during the experiment was supplemented with fresh fruit. This procedure resulted in healthy, well-conditioned animals that worked adequately on food-reinforced tasks. Water was continuously available in the home cage, which was located in a vivarium within the Walter Reed Army Institute of Research (WRAIR) microwave facility under a 12/12-h light-dark cycle (0630 on, 1830 off). Home cage temperature was maintained at 23.0-25.0 °C.

APPARATUS

Behavioral Apparatus. The monkeys were seated in a polyvinyl-chloride (PVC) pipe chair (Primate Products Co.) that was equipped with a plastic waste-collection catch pan. Each monkey wore a plastic collar and was properly acclimated to the pole-and-collar handling procedure (Anderson & Houghton, 1983). The chair was placed inside a large box (1.083 x .815 x .86 m) constructed of 5.08-cm thick Styrofoam sheeting. The box served to isolate the monkey from audible noise produced by the microwave apparatus. A window was cut in both the top (25.4 x 30.5 cm) and front (35.6 x 43.2 cm) of the box and covered with 3.2-mm thick Plexiglas© sheeting. The windows allowed light into the box and permitted monitoring the monkey by a Panasonic color video camera (Model 00160) with a video recorder (Model 00159). The removable front and back of the box was held in place with Velcro tape. A white-noise source (AM-1100, Soundolier, Inc.) at floor level produced a 75-dBA masking sound inside the chamber at the location of the chair. Output of the white-noise source was evaluated in one-third octave bands with a spectrum analyzer (RT Acoustics, Computational Systems Inc.). The majority of the energy was in the frequency range of 125-3150 Hz with a rapid drop off between 2000 and 5000 Hz. Background noise level was measured with an octave analyzer sound-level meter (Bruel & Kjaer, No. 2215).

The chair was equipped with plastic levers (7 cm long, 1.3 cm dia) that were mounted vertically, which when pulled by the monkey actuated fiber-optic light switches (Microswitch No. CJWZ- 3IIP-B). The fiber-optic switches were connected to light emitter/detectors (Microswith, No. FE7C-FR6M) with 15.2-m lengths of fiberoptic cable. Visual signals to the monkey where presented with fiber-optic cables and plastic diffusing screen mounted on the restraint chair at eye level. Spectral radiance of the light signals was measured with a spectral analysis system (Spectrascan Model PR-702AM, Photo Research Corporation). The 1960 C.I.E color coordinates were red signal, u = 0.5447 and v = 0.3443; green signal, u = 0.1281 and v = 0.3700; and white signal, u = 0.2684 and v = 0.3570. The distance from the monkey's eyes to the visual stimulus was 21 cm. The contingencies of the operant schedule as well as data collection and storage were controlled by a microcomputer (Zenith-248) and digital interface (Metrabyte, Dascon-1). Control programs were written in compiled BASIC language (Microsoft Corp., GW-BASIC©). The microcomputer was located in a control room just outside the anechoic chamber.

The monkeys head was located 2 m in front of the slotted waveguide at the center of the microwave beam. In this configuration, the long axis of the monkey's body was aligned parallel to the electric field vector. A pellet feeder (Foringer, 1 g) was mounted on a Plexiglas stand mounted on one side of Styrofoam box (80 cm above the monkey's head) and delivered monkey food pellets to the chair via a 62-cm length of Tygon tubing. A telethermometer (Yellow Springs No. 401) was used to record the ambient temperature within the Styrofoam box which ranged from 22.0 to 26.0 °C (± 1.4 °C *SEM*). A handheld portable hygrometer (Solomat, Model MPM 500e) was used to monitor relative humidity inside the Styrofoam box, which varied from 32 to 89%.

Microwave Pulse Apparatus Microwave exposures were conducted at the Walter Reed Army Institute of Research, Microwave Division, Forest Glen, Maryland. A Transformer Energized Megavolt Pulsed Output (TEMPO) axially extracted virtual cathode oscillator was used to deliver high-power microwave pulses (center frequency 3.0 GHz) to an anechoic chamber (3.65 X 3.65 X 2.43 m) via a slotted circular waveguide antenna. The TEMPO was designed at Sandia National Laboratories, DOE, Albuquerque, New Mexico. The microwave chamber was electrically shielded with double metal walls and completely lined with pyramidal absorbing material. An electrically shielded window on one side of the chamber allowed observation of the monkey during exposures.

Measurement of TEMPO microwave pulses in the anechoic chamber was accomplished using an open-ended waveguide (WR-284) terminated with a waveguide-to-coaxial-cable adapter. Samples of detected microwave energy were attenuated and applied to a crystal detector (NARDA, model 4503) and recorded on a transient digitizer (Tektronix, Model 7912). A typical TEMPO pulse is shown in Fig. 1. Repeat firing of TEMPO at a 7.5-s interpulse interval produced stable output, as shown in Fig. 2, with a slightly reduced power output (compared to Fig. 1). Power output over a series of 50 TEMPO pulses is shown in Fig. 3 Power density at the location of the monkey averaged 45.63 kW/cm², (± 2.29 kW/cm² *SEM*).

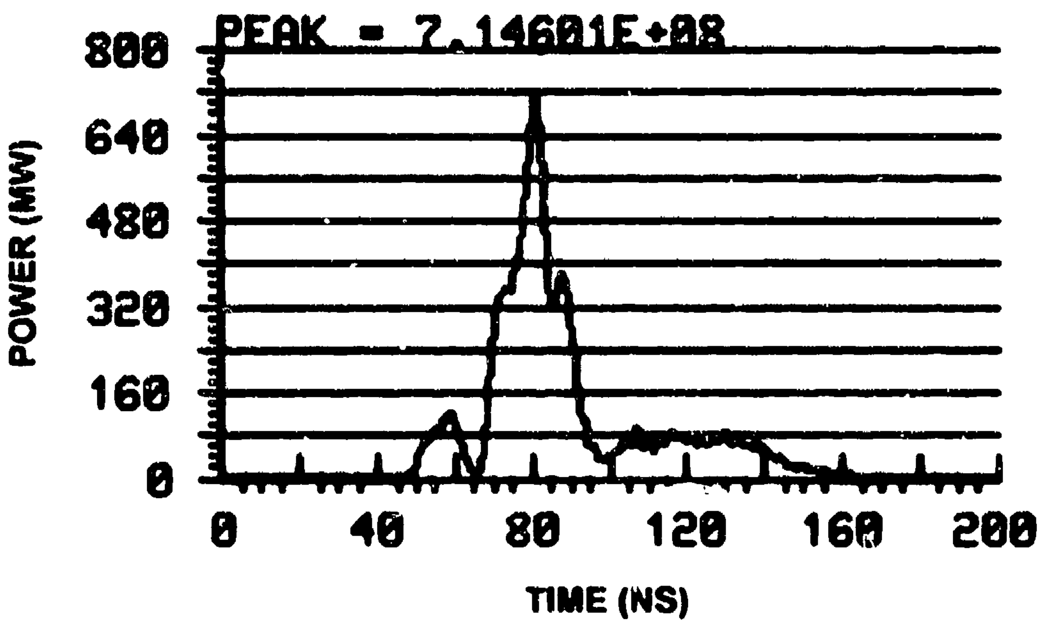

Figure 1. Typical waveform produced by TEMPO.

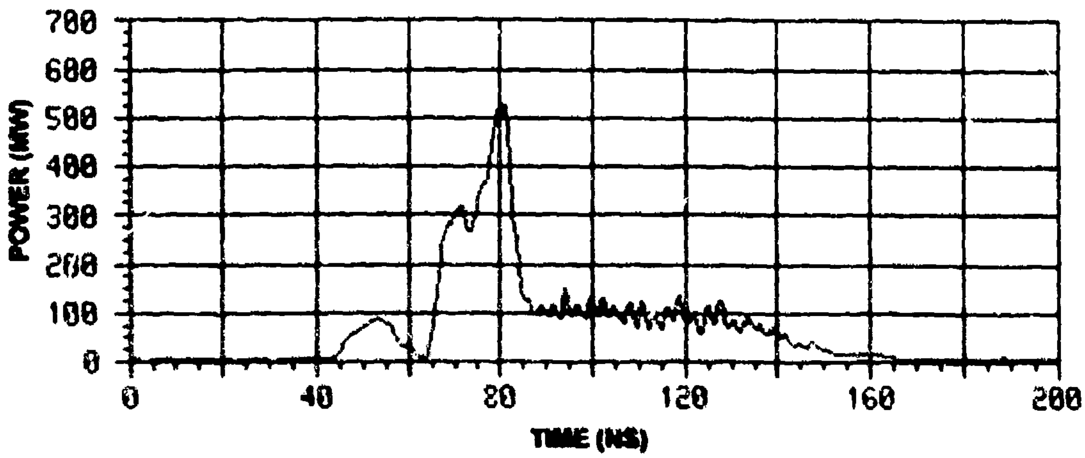

Figure 2. Waveform produced by TEMPO on repeated firing at a 7.5 s interpulse interval.

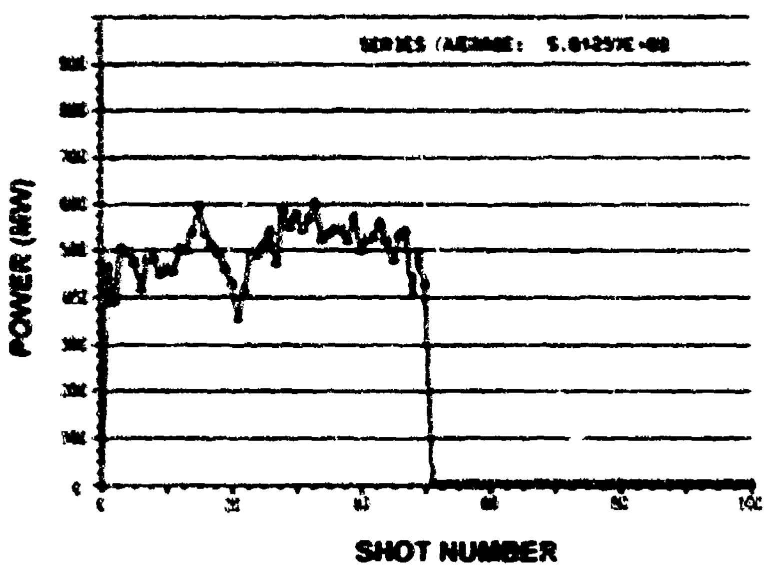

Figure 3. Variability in TEMPO output power over 50 pulses.

Measurements of the radiation pattern produced by the slotted waveguide antenna were accomplished using microwave power produced by a CW 1000 W klystron (Varian) and a three-axis mechanical scanner positioning a field power density probe (Holladay, Model 8003). The area scanned at 2 m from the antenna is diagramed in Fig. 4. Collection of data and automatic positioning of the power density probe was accomplished with a microcomputer (Zenith, Model Z248).

PROCEDURE

Behavioral Training. Four monkeys were trained on a multiple schedule using visual signals as discriminative stimuli. The schedule was divided into two main components. In the first component (VI component), a red light (peak spectral radiance 770 nm) was associated with responding on the right lever during a variable interval (20 s average, 1-84 s range) schedule. In the second component, green and white lights were associated with responding on the left lever (choice-reaction-time component). A response on the left lever in the presence of a green light (peak spectral radiance 534 nm) resulted in a food pellet, whereas a response on the left lever when the white light was illuminated resulted in a 10-s time-out period and no food pellet. The visual signals (green and white) were given in random order for 1-s durations at the end of each variable interval. Behavioral sessions were 62 min duration and were divided into three 20 min components (pretest, exposure, posttest) with a 1-min extinction period between each component.

Monkeys were initially given 8 weeks of training at the Naval Aerospace Medical Research Labortory (NAMRL) in a sound isolation chamber followed by daily training sessions (5 days per week) for 8 weeks in the styrofoam isolation box prior to air transport to Walter Reed, Forest Glen, Maryland. After arrival, the monkeys required approximately six training sessions to reestablish stable performance. The monkeys were then exposed to TEMPO microwave pulses or sham microwave pulses, while performing the task, using a repeated measures experimental design with each subject serving as its own control. Repeated-measures analysis of variance and multiple comparisons were used to test for significant effects on four behavioral response measures: right-lever response rate, left-lever reaction time, postreinforcement pause time, and postchoice pause time (ANOVA in the MGLH module; SYSTAT, Inc., Wilkinson, 1990).

Microwave Exposure. Following the development of stable behavioral performance, microwave and sham exposures were given during the middle 20-min component of the daily session. Pulses, 20-60 ns in duration were given automatically every 7.5 s. Sham exposures were conducted in a similar manner, except microwaves were blocked from the monkey by covering the slotted waveguide antenna with screen wire (1.5-cm square mesh) to prevent the propagation of microwave pulses into the chamber.

Whole-body Dosimetry. Estimates of whole-body average SAR at 3.0 GHz were obtained using the CW klystron source and a plastic 3-liter soft-drink bottle (27 cm high, 12 cm dia) filled with a 0.9% saline solution. A Holladay field power density meter (No. 3003) and field probe (No. 007) were used to set the power density at the location of the monkey chair at 100 mW/cm². The bottle was then placed in the chair or on Styrofoam blocks in the same location after the chair was removed. The bottle was then irradiated for 180 or 360 s. Temperature of the bottle was measured before and after microwaves exposure. Saline in the bottle was stirred by inverting the bottle three times after removal from the chair and prior to measuring the temperature. The SAR was then calculated using the following formula: SAR (W/kg) = cT/t, where T is the temperature change in degrees Celsius, c is the specific heat in J/kg/°C, and t is the exposure time in seconds. Estimates of SAR using this procedure are given in Table 1. Based on the exposures shown, we used the normalized SAR of 0.0465 W/kg per mW/cm² to calculate a peak whole-body SAR during TEMPO exposures of 2.21 MW/kg (SA per pulse was 1.3 J/kg).

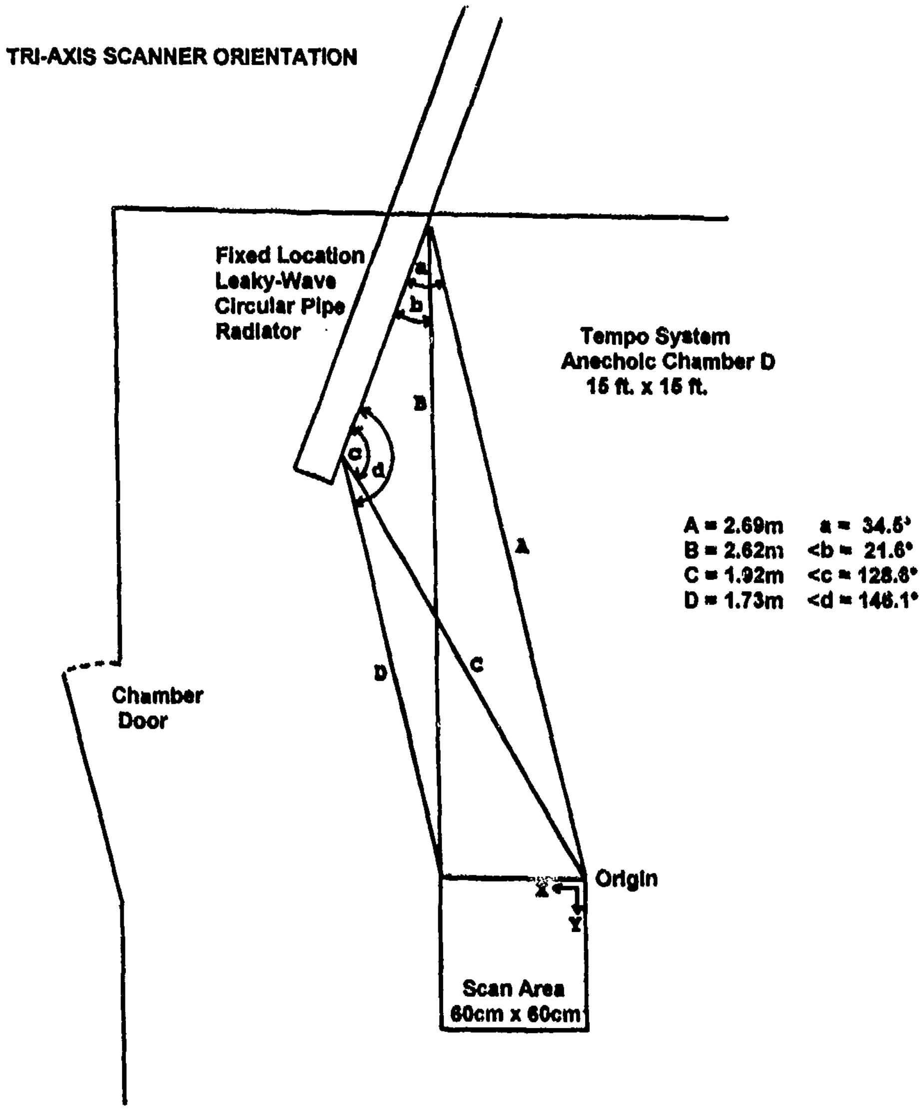

Figure 4. Schematic of area in anechoic chamber scanned during power density measurements.

Table 1. Temperature rise and SAR of 3-liter bottle.

Exposure condition	Exposure time (s)	Temperature rise °C	SAR W/kg
Chair	180	0.20	4.65
	180	0.20	4.65
	180	0.20	4.65
	360	0.40	4.65
	360	0.40	4.65
	360	0.40	4.65
No chair	180	0.20	4.65
	180	0.20	4.65
	180	0.30	6.98
	360	0.40	4.65
	360	0.40	4.65
	360	0.40	4.65

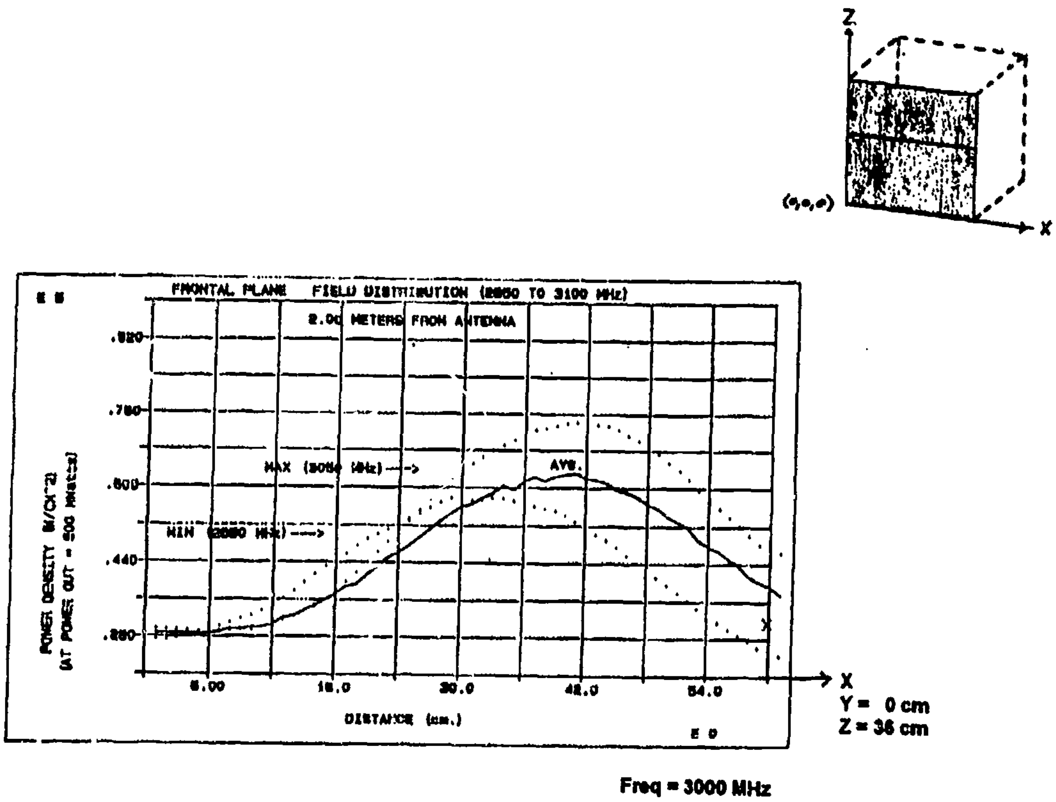

Figure 5. Power density across area scanned (see Fig. 4).

Part-body Dosimetry. An estimate of the local SAR in a monkey model was determined by Dr. Chun Y. Moon at WRAIR using a 5.09-kg bag monkey model, similar to the man-sized bag model used by Olsen & Griner (1989), and filled with simulated muscle tissue (Chou, Chen, Guy, & Luk, 1984). The monkey model was mounted in the PVC chair and placed inside the Styrofoam box. A microwave-compatible temperature monitor (NARDA, Model 8011B, Probe Model 8001B) and x-y recorder (Kipp & Zonen, Model BD90) were used to determine local SAR values within the monkey bag model. Locations measured in the model, at depths of 2-3 mm, were the face, neck, chest, and center of head (head dia was 8 cm, probe placed 4 cm deep). The monkey model was placed 2.05 m from the slotted waveguide antenna in a field power density of 100 mW/cm². Exposures were 20 s in duration. The average temperature rise at each sample site, with and without the PVC chair, are listed in Table 2. From the temperature measurements, SAR at each sample site was calculated for the CW 3.0 GHz exposures as well as for TEMPO exposures (Table 3).

Table 2. Temperature rise at each sample site.

Sample site	Chair temperature rise °C	No chair temperature rise °C
Face surface	0.0229 0.0213	0.0539
Neck surface	0.1035 0.1072	0.0644
Chest surface	0.1493	0.2098 0.2123
Head center	0.0010	0.0028

Table 3. SAR for CW and TEMPO exposures.

SAR sample site	<u>CW</u> chair actual SAR W/kg	<u>CW</u> no chair actual SAR W/kg	<u>TEMPO</u> chair estimated peak SAR MW/kg
Face surface	5.58 5.19	9.48	2.55 2.37
Neck surface	19.50 18.85	11.31	8.90 8.60
Chest surface	27.33	21.47 37.32	12.47
Head center	0.020	0.049	0.09

Ionizing Radiation Dosimetry. The TEMPO produces significant levels of soft x rays from which the monkey must be protected by lead shielding. To determine the continued effectiveness of the shielding, each monkey was assigned a badge and Thermo Cuminescent Dosimetry (TLD) for cumulative exposure across all sessions as well as another badge and TLD to measure x-ray exposure during a single session. The cumulative exposure TLD dosimetry ranges were .543 rem to 1.645 rem (Mean .965, ± .101 *SEM*). Single session ranges were 0.009 to 0.046 rem (Mean .016, ± .005 *SEM*).

Statistical Analyses. The independent variables of a) sham and TEMPO exposure and b) session component (pre, exposure, post) were analyzed with a completely within mixed-model 2 x 3 repeated-measures analysis of variance (ANOVA in the MGLH module; SYSTAT, Inc.) on each of the dependent variables (Wilkinson, 1990). All ANOVA significance levels were calculated with a Geisser-Greenhouse correction (Wilkinson, 1990). Post-hoc multiple comparison of means ($p < 0.05$) was conducted using the Tukey HSD test (Kirk, 1968).

RESULTS

All monkeys performed as expected during the training at NAMRL and baseline phases of the experiment at WRAIR. The variable interval procedure produced steady, rapid responding on the right lever interrupted by occasional responses on the left lever during the green or white lights. The monkeys emitted occasional incorrect responses on the left lever during the white light followed by a time out, but these stabilized to only a few per session.

Response rates in the interval prior to each green light presentation for Monkey #148 are shown in Fig. 6. The top portion of the figure shows response rate for each session component for a sham exposure. The bottom portion of the figure shows response rate during exposure to TEMPO pulses. There is a drop in response rate on the first and last trial of sham exposure and exposure to TEMPO pulses. However, as can be seen, the drop is only during that first and last exposure.

Reaction time to each green light presentation for Monkey #148 are shown in Fig. 7. The top portion of the figure shows reaction times for each session component for a sham exposure. The bottom portion of the figure shows reaction time during exposure to TEMPO pulses. There is little change in reaction time during sham exposure or exposure to TEMPO pulses.

Review of videotapes made of all exposures and sham exposures showed that monkeys exhibited a distinct orienting response to the first TEMPO pulse whether it was delivered as an exposure or sham exposure. They also exhibited an orienting response upon cessation of the pulses. The change in response rate is undoubtedly due to the noise produced by the TEMPO during both sham and exposure to TEMPO pulses. After the first pulse, however, response rates remained at the same level as during preexposure and presham components until cessation of pulses.

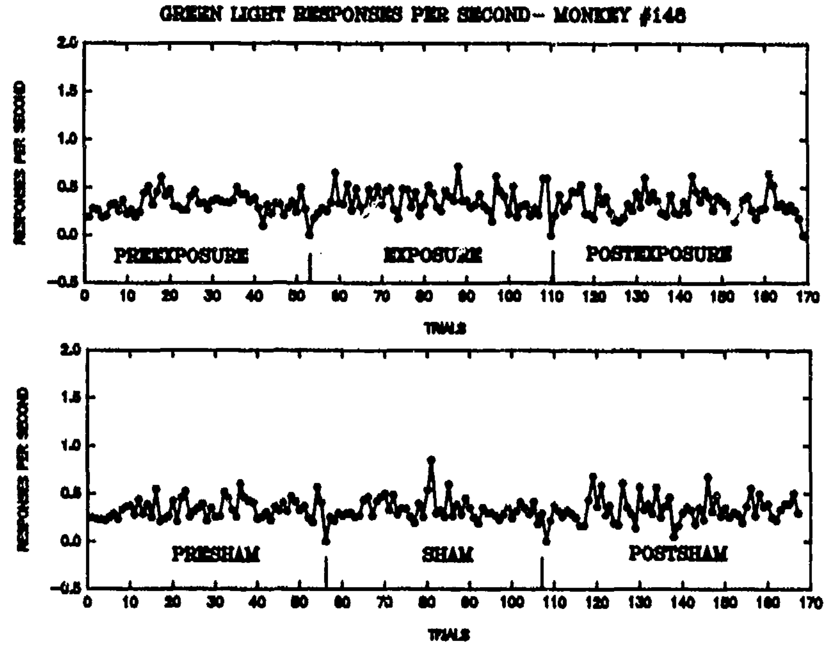

Figure 6. Response rate during each interval (trial) prior to onset of the green light for sham exposure (bottom panel) and exposure to TEMPO pulses (top panel).

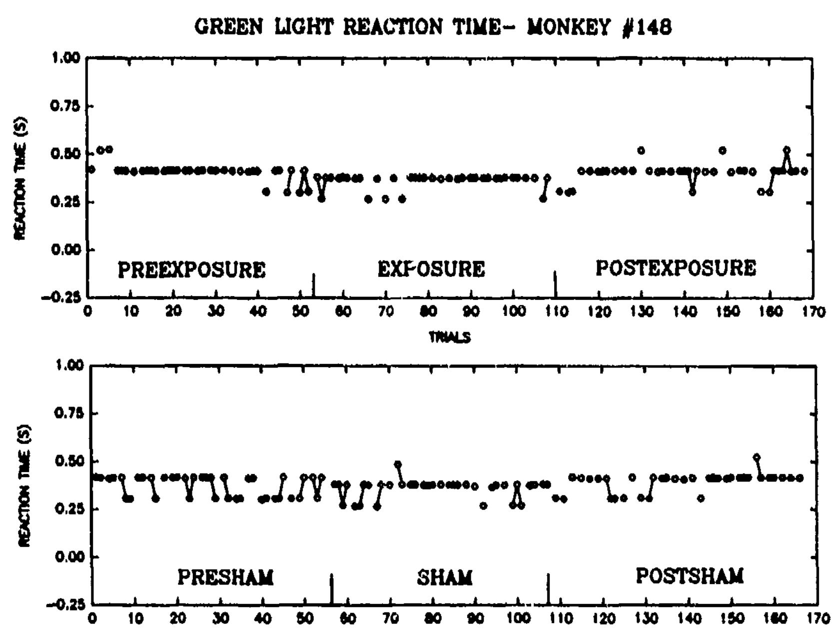

Figure 7. Reaction time to onset of green light for sham exposure and exposure to TEMPO pulses.

Mean total responses emitted on the right lever and mean reaction time on the left lever are shown in Fig. 8. The TEMPO pulses did not significantly alter either measure of performance. Separate ANOVAs for each measure showed that total responses and reaction times during sham and TEMPO pulses did not differ significantly. Both measures across the three components (preexposure, exposure, postexposure) also did not change ($p > 0.05$). In addition, there was no interaction between TEMPO and sham exposures over the three session components ($p > 0.05$).

Postreinforcement pause time after delivery of a food pellet and postchoice pause after a white light did not change during sham or TEMPO pulses (Fig. 9). Post reinforcement pauses were quite stable from session to session and during each component of sham and TEMPO exposure sessions. Postchoice pauses, however, were quite variable during training and remained variable during sham and TEMPO exposure sessions as shown in Fig. 9. The ANOVAs for both measures showed no significant differences between sham and TEMPO exposures, across session components (preexposure, exposure, postexposure), or the interaction between session components and exposures ($p > 0.05$).

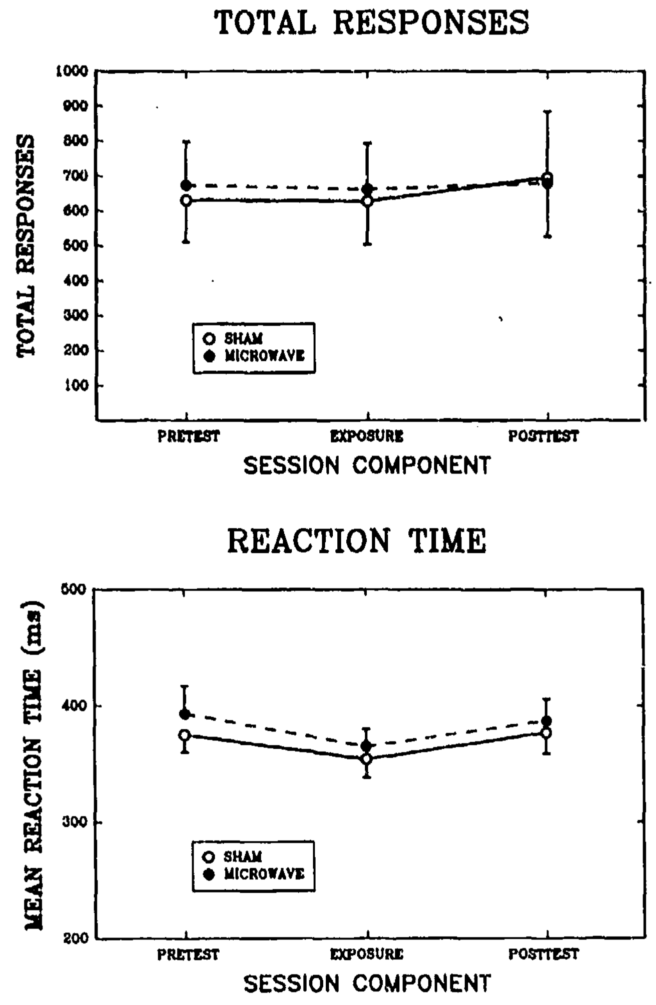

Figure 8. Mean total responses (± *SEM*) on right lever and reaction time on left lever prior to, during, and after microwave pulse exposure.

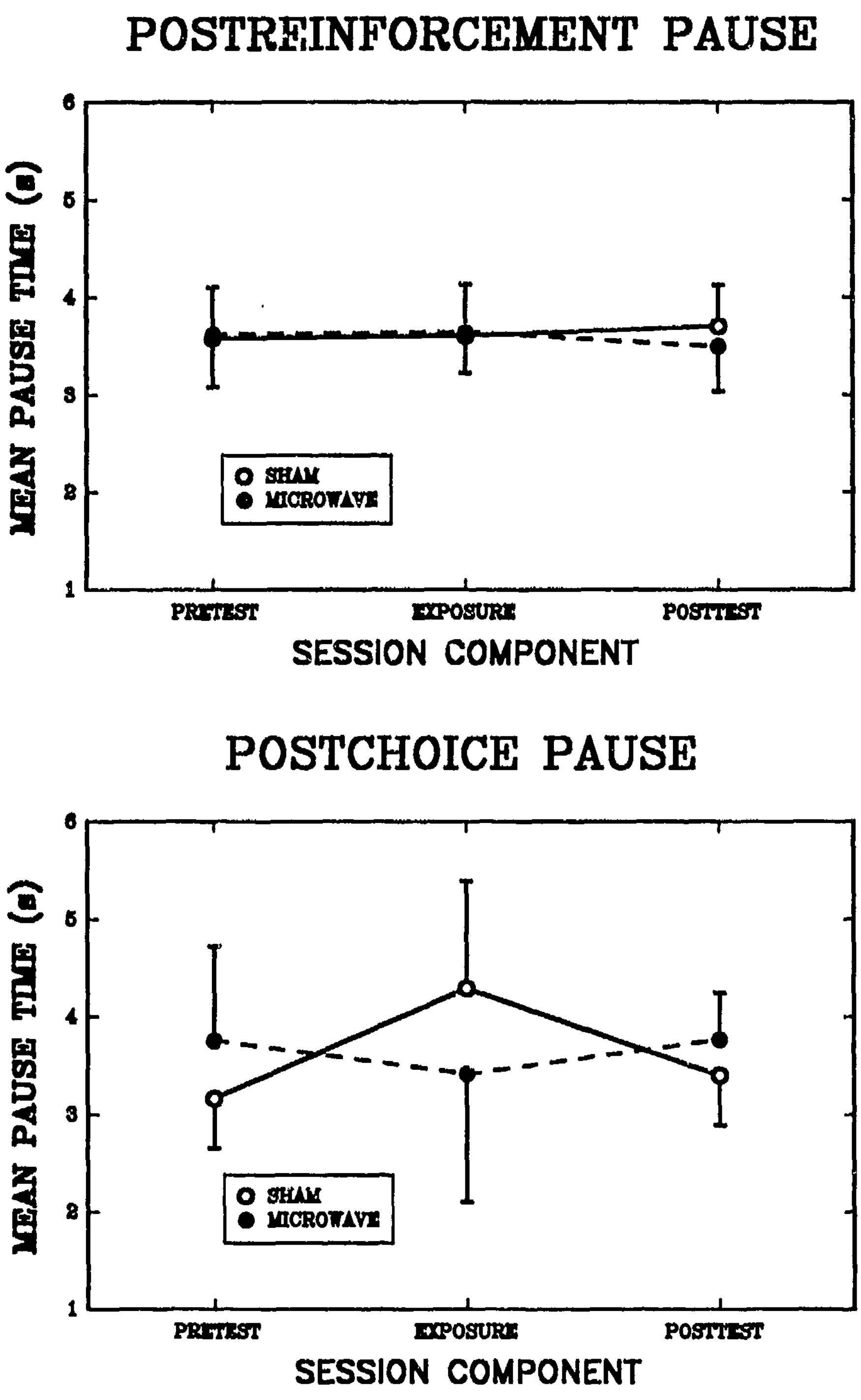

Figure 9. Mean postreinforcement pause time (± *SEM*) and mean postchoice pause time (± *SEM*).

DISCUSSION

The results of this experiment show that exposure to short high-peak-power microwave pulses with very high peak SARs but low average SARs did not significantly alter a well-trained behavior in the rhesus monkey. This outcome agrees with the results of previous experiments with TEMPO (D'Andrea et al., 1990). Very high peak power density used in this experiment of 45.63 kW/cm^2 produced peak whole-body SARs of approximately 2.21 MW/kg. This far exceeds limits set by the current safety standard (IEEE, 1991) of approximately 2.65 kW/cm^2 with no effect on a complex monkey behavior. The average whole-body SARs produced during this experiment (< 0.10 W/kg), and the previous experiments (< 0.03 W/kg), were well below the average whole-body SAR threshold (4 W/kg) known to disrupt behavioral performance (D'Andrea, 1991; D'Andrea & de Lorge, 1990; de Lorge, 1984). This outcome suggests that the high-peak-power limits set by the current safety standard are effective. In conclusion, our research supports the exposure limit set by the current safety standard.

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13. ABSTRACT *(Maximum 200 words)*

The development of adequate safety standards for exposure to microwave radiation requires an extensive database which provides information on frequency, power, and modulation characteristics. This study was conducted to provide information on the behavioral effects of high-peak-power microwave pulses produced by an axially extracted virtual cathode oscillator. This pulsed microwave source, TEMPO[1], was located at the Walter Reed Army Institute of Research and for this study was configured to produce high-peak-power 3.0 GHz microwave pulses, 20-60 ns pulse duration with a 7.5 s interpulse interval. To investigate the behavioral effects of the high peak power pulses, four male rhesus monkeys (*Macaca mulatta*) were trained on a operant color discrimination task for food pellet reward. The task was twofold requiring monkeys to pull one plastic lever on a variable interval schedule (VI-25 s) and then respond to color signals and pull a second lever to obtain food. During the behavioral task, the monkeys were exposed to microwave pulses produced by TEMPO. Peak field power densities averaged 45.63 kW/cm^2, which produced a peak whole-body specific absorption rate (SAR) of approximately 2.21 MW/kg (specific absorption (SA) per pulse was 1.3 J/kg). Average whole-body SAR, however, was low due to the short pulse duration and long interpulse interval. Behavioral performance on either component of the task was not altered significantly by the high-peak-power pulses.

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Transformer Energized Megavolt Pulsed Output (TEMPO)

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